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TEMPERATURE MEASUREMENTS IN FDL 50-MEGAWATT ELECTROGASDYNAMIC FACILITY

H. N. Olsen, F. L. Kelly, and G. Bedjai

Plasma Sciences Laboratories, Inc.

October 1970

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FOREWORD

The research reported herein was sponsored by the Arnold Engineering Development Center (AEDC) as an added Task to contract F40600-69-C-0007, Air Force Systems Command (AFSC), under Program Element 65701F, Project 4344, Task 12.

The results of the research were obtained by Plasma Sciences Laboratories on the Air Force Flight Dynamics Laboratory (AFFDL) Electrogasdynamic Test Facility at Wright-Patterson Air Force Base, Ohio. The experimentation was performed from June 15 to June 19, 1970, and the manuscript was submitted for publication on July 15, 1970.

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The investigation was conducted under the direction of Dr. H. N. Olsen, serving as Principal Investigator, Mr. F. L. Kelly assisted in performing the experimental work and Mr. G. Bedjai assisted with the data processing and report preparation.

This technical report has been reviewed and is approved.

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ABSTRACT

Temperatures in the free stream of the 50 MW Electrogasdynamic Test Facility at WPAFB have been determined from experimentally measured radial intensity profiles of the electron continuum. Static plasma pressures were 10 and 20 atm in flowing air and measured temperatures ranged from 3800°K to 5400°K. A spectral probe defined by the optical path of a 1/4 meter grating spectrograph and focussing lens was traversed across the shock cone of the plasma before and after insertion of test samples. Calibration curves for the detector which were previously developed under the parent contract were used for relating the measured intensity to temperature. The results indicate that the nitric oxide concentration in the plasma is lower than the equilibrium value expected at these temperatures.

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SECTION I
INTRODUCTION

As an added Task in the work statement of Air Force Contract F 40600-69-C-0007, a brief series of experiments was carried out on the 50 megawatt electrogasdynamic facility in the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base, Ohio. The experiments performed in non-interfering pick-a-back fashion during routine operations of the facility, were of necessity very limited in scope and were expected only to demonstrate the feasibility of applying the spectral diagnostic methods developed earlier at Plasma Sciences Laboratories, Tarzana, California for temperature measurements in the free stream of the jet.

This report describes the apparatus, experimental methods and the results of a series of tests designed to investigate the levels of intensity and static temperature in the free stream of the arc heater operating at 40MW with a 1.8 mach cone and static exit pressures of 10 and 20 atm. The parent report describes in detail the preliminary calibration of the continuum temperature profile used to convert the measured intensities to static temperatures.

SECTION II
APPARATUS

The spectral probe, shown in its operating position at the 45° view port above the arc heater in Fig. 1, consisted of the 1/4 meter grating spectrograph which was designed for probing the 2MW seeded arc heater at AEDC. Details of the spectrograph are given in AEDC-TR-69-275[1]. The spectrograph and focussing lens were rigidly mounted together on a transport table to constitute a moving spectral probe defined by the optical axis of the combined system. The system was oriented such that the probe moved in a plane parallel with the face of the nozzle and could be traversed a total distance of 1.9 inches. The speed of travel was such that the entire jet could be

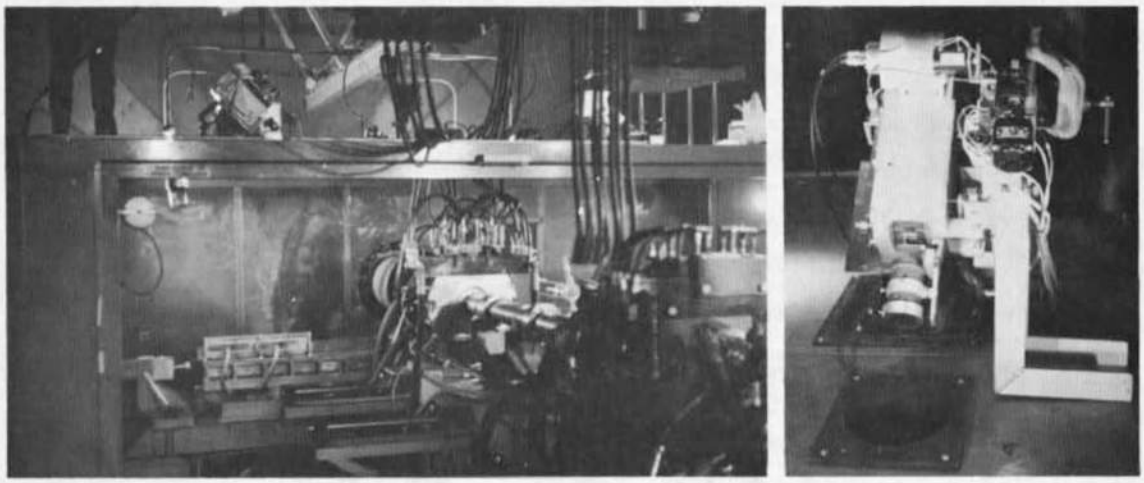

Fig. 1. Spectrographic probe shown mounted on FDL/50MW facility.

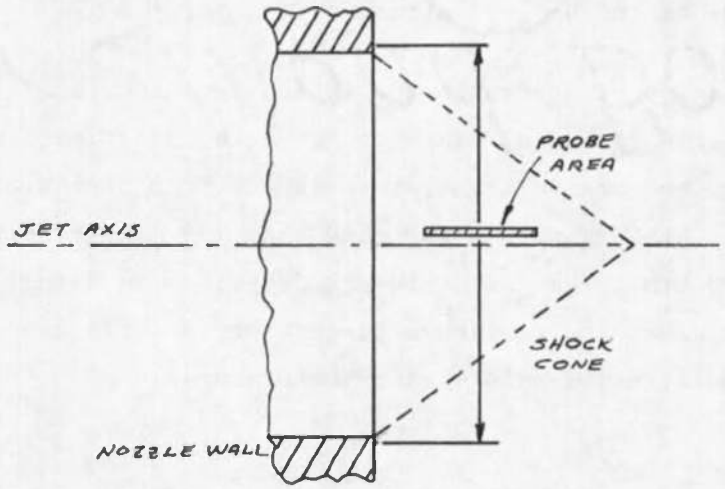

Fig. 2. Schematic of nozzle, shock cone, and probe showing relative size and path of travel.

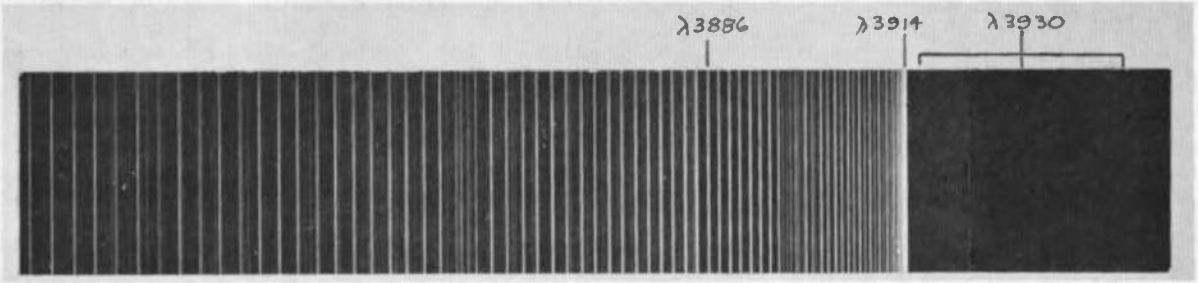

Fig. 3. λ3914 Å, $N_2^+(1-)(0,0)$ band system showing location of wavelength increment used as spectral probe.

traversed in 15 sec. The position of the probe was translated to the x-axis on an x-y recorder by means of a linear potentiometer attached directly to the transport table. Intensity signals were read out from a 1P28 photomultiplier on the y-axis of the recorder through an operational amplifier.

Because of interference with existing experimental apparatus the spectral probe could not be mounted directly over the jet as was initially planned so as to keep the source-to-lens distance as small as possible. The longer distance imposed by the alternative 45° mounting resulted in an image reduction of 16:1. With the smallest aperture on the 50μ entrance slit of the spectrograph this resulted in an effective probe area in the source of 0.33 x 0.033 inch; the longer dimension being oriented parallel with the jet axis. The area of the probe relative to the nozzle opening and estimated shock angle is shown in the diagram of Fig. 2.

The exit slit of the spectrograph was set to a width of 200μ which represents a wavelength increment of 28 Å. Since all quantitative measurements were made in the continuum this broad slit was used to assure sufficient signal. A rotary potentiometer, geared directly to the wavelength micrometer screw, which could be remotely driven, provided a dc signal which could be interchanged with the transport table position signal to provide a wavelength readout with linear dispersion on the x-y recorder. Wavelength calibration was made on the spot by means of a low pressure mercury lamp temporarily mounted immediately in front of the entrance slit. By interpolation between known mercury spectral lines the proper setting of the micrometer screw (indicated by position on the x-axis of the recorder) could be determined for λ3930 Å and periodic checks of the setting could be made quite readily.

With the spectrograph set at the proper wavelength the position of the spectral probe, defined by the optical axis formed by the internal optics and the external focussing lens, was adjusted to move in a plane parallel with the nozzle surface with probe center 5/16 inch down stream from it. This adjustment was made by inserting a

small tungsten ribbon lamp into the nozzle such that the filament which was about 1/2 inch long and 1/16 inch wide extended from the surface of the nozzle along the jet axis. While traversing the probe the position of the signal spike from the tungsten lamp could be adjusted to appear at the center of the x-axis on the recorder. By adjusting the x-axis gain of the recorder the pen travel corresponding with the nozzle diameter could be adjusted to cover a convenient portion of the useable x-axis. With the spectral probe adjusted to the center of the tungsten filament the location of its center could be determined by moving an opaque straight edge along the filament toward the nozzle until the signal level was reduced to half-value. In this way the position of the probe relative to the nozzle surface and its resolution in the source (see Fig. 2) were determined.

The tungsten lamp served as an intensity calibration standard as well as an alignment source. The lamp operating at a current of 8 amp was pre-calibrated at PSL against a low current carbon arc standard. At $\lambda 3930$ Å, $dI_w/d\lambda$ for the lamp was determined to be 1.15×10^{-4} watt/(cm^2-sr-Å). With the spectral probe adjusted as it was used in probing the jet, the pen displacement Δ_ℓ, caused by traversing the calibration lamp when placed on the jet axis was used in the following expression:

$$K = \frac{\lambda^2 \frac{dI_w}{d\lambda}}{c \, \Delta_\ell} \quad \frac{\text{watt}}{\text{cm}^2\text{-sr-sec}^{-1}\text{-chart unit}}$$

to determine the calibration factor needed to put the measured intensity on an absolute scale. Note that the displacement caused by the tungsten lamp must be in the same chart units as that measured for the jet.

The arc heater, which is described in detail in publications of the Air Force Flight Dynamics Laboratory, was operated four times during this test series at two plenum pressures, i.e., 1500 and 900 psi, with corresponding static exit pressures in the shock cone of 20 and 10 atm. Total power levels were of the order of 32 MW and average

total enthalpy of ~2500 Btu/lb.Arc currents were ~ 2600 amps. The nozzle exit diameter was 1.1 inch and the mach number about 1.8. The longest continuous run was about one minute. Exhaust was into the air and operation was under routine commercial testing of ablative samples.

SECTION III
EXPERIMENTAL PROCEDURES AND RESULTS

The first of the four tests was only used for visual observation through closed circuit TV. This observation did serve to give us a feeling for the relative geometry of the jet and provided a crude estimate of the level of intensity to be expected. The necessary change in plans for mounting the spectral probe at the 45° port rather than overhead made it impossible to operate the probe for radial profile measurements on the second firing (Run 14-4). In order to obtain some quantitative information from this second run the spectral probe was mounted in fixed position and aimed as nearly on the jet axis as could be pre-determined during the short period between runs. During this run the photomultiplier voltage and recorder y-axis gain were adjusted to give a useable chart deflection. After the samples had traversed the jet the wavelength drive of the spectrograph was then engaged so that the exit slit was effectively moved from the λ3930 Å position of the continuum toward shorter wavelengths into the region of the $N_2^+(1-)(0,0)$ λ3914 band system which is shown as recorded in high dispersion for a 1 atm nitrogen subsonic jet in Fig. 3. As was to be expected the band system could not be observed above the background continuum. The level of the continuum intensity observed during this cursory run was found to be $\sim 10^{-15}$ watt/$(cm^2\text{-sr-sec}^{-1})$. This corresponds with static temperatures in the 4000-5000°K range rather than 2000 to 3000°K as was anticipated from preliminary discussions.

The third run, number 14-5, was essentially a duplicate of Run 14-4 so that the procedure was to use only the position drive of the probe with the wavelength pre-set to λ3930 Å and the probe initially

positioned on the jet axis. The operating pressure was 1600 psi with an approximate exit static pressure of 20 atm. A complete radial profile was successfully recorded during this run. Wavelength and intensity calibrations were made before and after each run to assure that vibration had not changed the probe alignment during the run.

The final run number 14-6 was made at the lower pressure of 900 psi (10 atm static exit pressure). Because of the longer operating time permissible at this lower pressure a complete radial profile of the intensity could be obtained at the beginning and end of the run. These two radial profiles, as recorded, are shown in Fig. 4. The upper trace was made at the start of the run. The apparent reproducibility in fluctuations cannot be explained as due to chattering in the drive mechanism which has been checked to be smooth when scanning a stable source. An additional wavelength scan into the region of the band system was made during this run and also showed the discrete radiation to be masked by the continuum.

The experimental results are presented in the form of radial profiles of the emission coefficient for the continuum which are obtained by the usual inversion [2] of the integral equation (Abel integral) which relates measured intensity to the local emission coefficient. The results for the two pressures are shown in Fig. 5. Smooth average curves were drawn through the measured intensity profiles before inversion. The double curves shown for the 10 atm case represent averages for the upper and lower profiles of Fig. 4. No attempt has been made at this stage to analyze the fluctuations. Much more rapid scanning than is presently available would be needed to differentiate between spatial and temporal fluctuations.

The transformation of the measured radial profiles of continuum emission coefficients to temperatures requires proper calibration of the continuum for air plasmas at elevated pressures. Such a calibration for atmospheric pressure has been made during the past year at

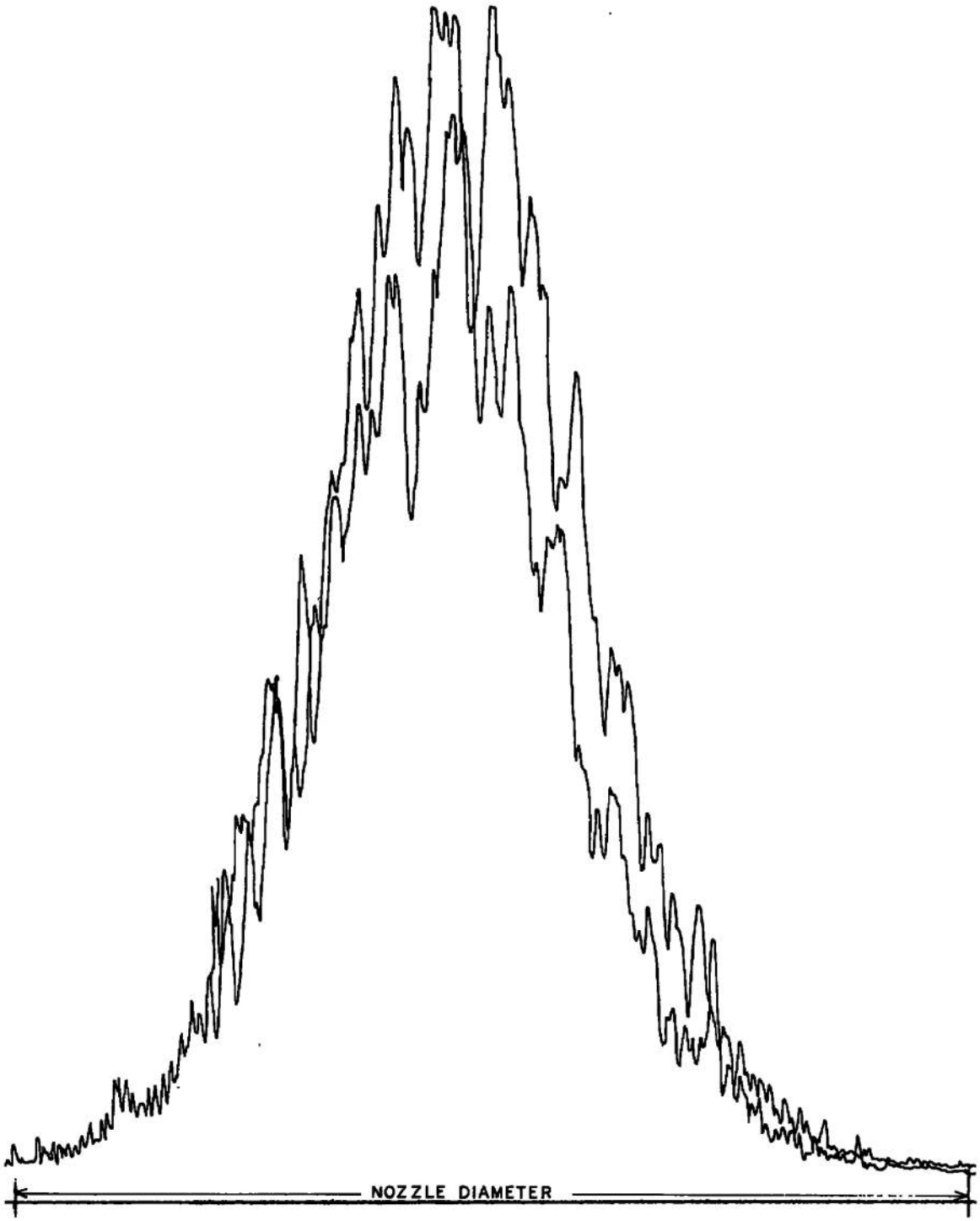

Fig. 4. Radial intensity profiles measured at beginning and end of Run 14-6.

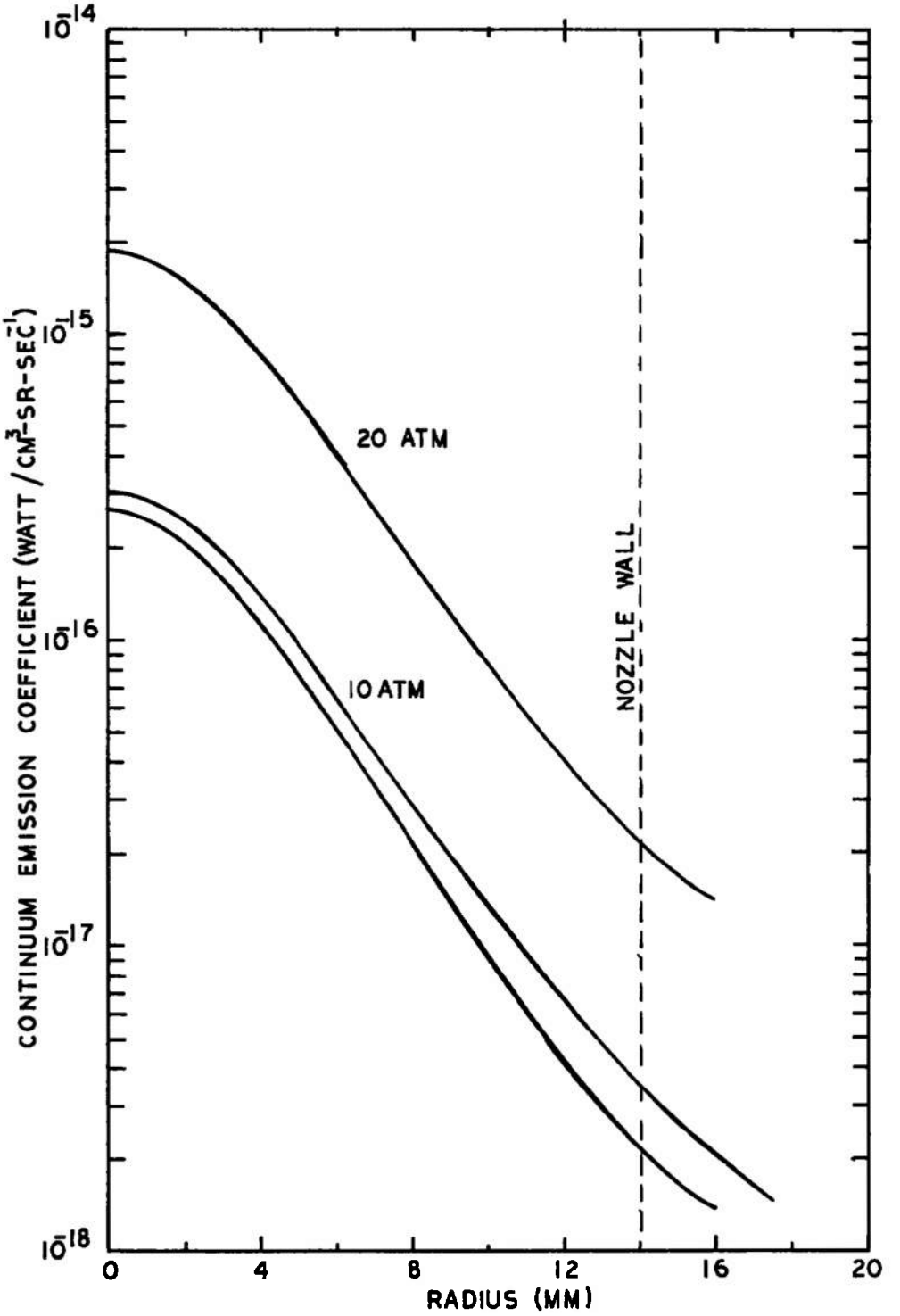

Fig. 5. Radial profiles of continuum obtained by inversion of measured intensity profiles; the two profiles for 10 atm plasma correspond with the two intensity profiles of Fig. 4.

PSL and can be used along with computed plasma compositions to obtain at least approximate temperature profiles for these measured intensities. This procedure is discussed in detail in the following section.

SECTION IV
DISCUSSION

Experimentation during the past two years conducted by the scientific staff of PSL has clearly shown that the electron continuum emitted by subsonic and supersonic jets in pure air and nitrogen at temperatures below 8000°K is considerably higher than can be explained by any existing theories. In the subsonic nitrogen jet at atmospheric pressure the discrepancy was found to be more than five orders of magnitude.

In the ranges of temperature and pressure encountered in these tests discrete band and atomic spectral line radiation cannot be separated from the background continuum. The continuum must, therefore, be used in any spectral diagnostic method. Since the theoretical relationship between the continuum and equilibrium static temperature cannot be relied upon, it is necessary to make an independent temperature calibration of the measured continuum. This was the object of the past year's work under this contract and the results are discussed in the parent report.

Continuum calibration could only be made at temperatures above 4000°K in atmospheric pressure plasmas where atomic spectral lines and portions of the neutral and ionized molecular band system could be observed and used to determine the temperature of the plasma as a function of radius. For the nitrogen plasma at 1 atm and temperatures above 5000°K equilibrium was demonstrated by the agreement in the temperatures determined from the several species of radiation when using the computed equilibrium compositions. At temperatures below 5000°K the emission coefficient of the continuum has been shown to be empirically related to temperature through the temperature dependence of the computed number densities of neutral molecules,

N_2, and electrons, N_e, as $\epsilon_{cont} = kN_2(T)N_e(T)$ where $k = 2.2 \times 10^{-48}$. In this calibration the temperature was determined from the simultaneously measured increment near the band head indicated in Fig. 3. For temperatures above 4000°K the direct calibration can be used. Below this temperature, where the band blends into the background continuum, the empirical curve must be used.

There are logical reasons for assuming that the neutral molecules will be equally effective in retarding the free electrons in air as in nitrogen and that the proportionality constant determined for the nitrogen plasma may be assumed to relate the continuum emission coefficient of an air plasma to its computed equilibrium number densities and, therefore, to temperature. From published absorption cross-sections for nitrogen and oxygen the contribution to the continuum due to the retarding effect of the oxygen molecule on the free electrons in the air plasma is estimated to be at least an order of magnitude lower than for the nitrogen molecules. At the temperatures considered the oxygen atom can be completely neglected as was also the case for the nitrogen atom.

An attempt to apply the above assumptions to a reconstituted "air" plasma, i.e., a nitrogen plasma to which oxygen is added to form a 79-21% nitrogen-oxygen mixture, has shown a discrepancy between temperatures determined from the ion band system and from the continuum computed in the above manner from the air plasma composition with $k = 2.2 \times 10^{-48}$. This discrepancy is indicated in the composite plot of Fig. 6. The horizontal lines, labeled with radius as parameter, represent pairs of band and continuum emission coefficients measured simultaneously in the mixed plasma at atmospheric pressure. Intersections of these lines with the equilibrium air curves show a total temperature discrepancy of $\sim$2200°K. The maximum error in temperature determined from the continuum alone would be $\sim$1500°K.

A comparison of the measured emission coefficients with equilibrium curves for the pure nitrogen plasma at the same total pressure

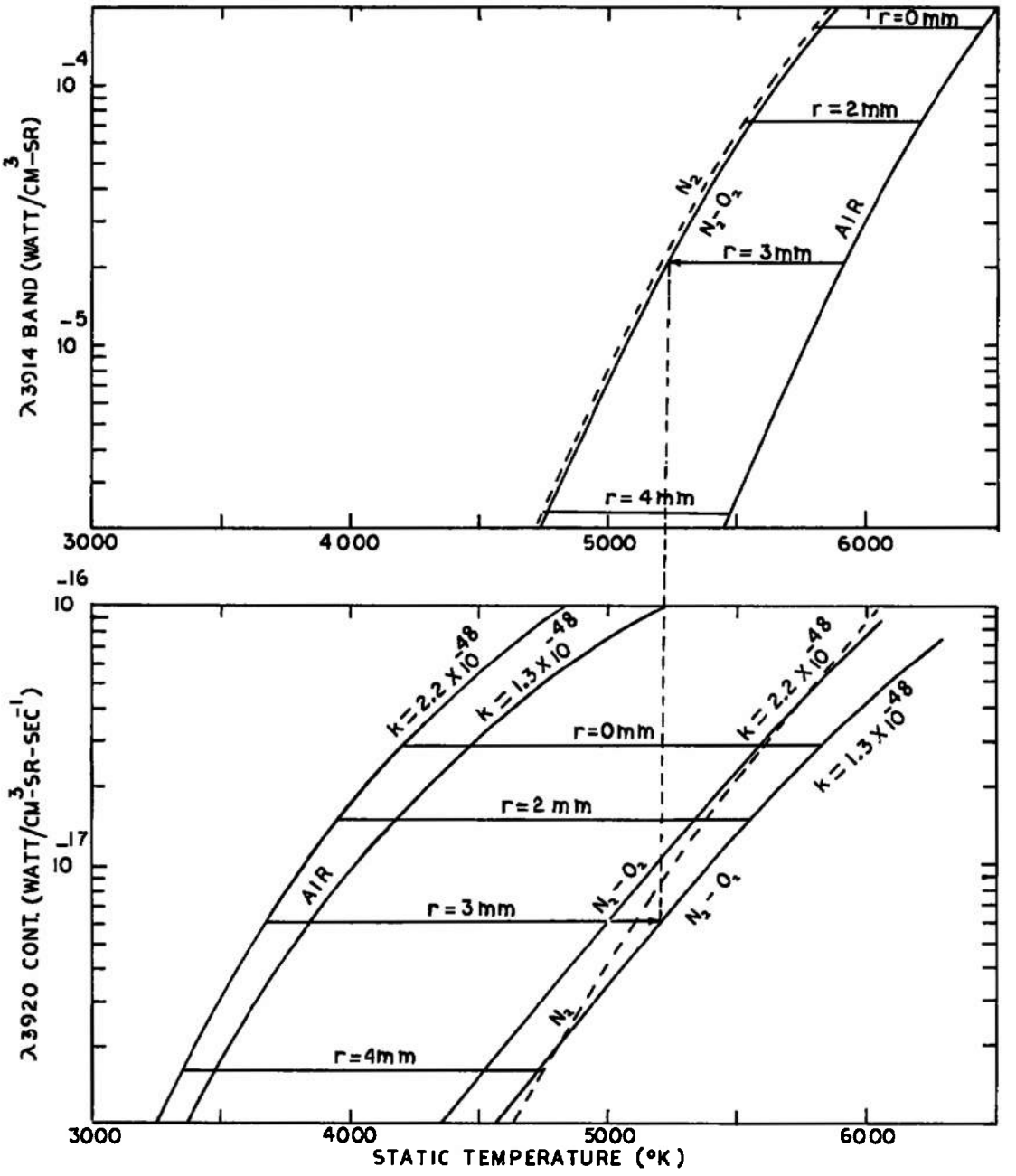

Fig. 6. Comparative plots of band system and continuum for 1 atm air, nitrogen and nitrogen-oxygen plasmas.

(dashed curves of Fig. 6) shows considerably less temperature discrepancy than the equilibrium air curves. Furthermore, a comparison of the air and nitrogen plasma compositions shows that the main contribution of electrons in the air plasma is the reaction $NO \rightleftharpoons NO^{+}+e$. The reaction which produces the NO in the air plasma is known to be slow in equilibrating and has been found in plasma chemistry experiments to yield much less than the equilibrium concentration. This led to the suspicion that the mixed plasma is really only a mixture consisting of 79% of the particles of a one atmosphere nitrogen plasma and 21% of the particles of a one atmosphere oxygen plasma. The ϵ vs T curves for the assumed mixed plasma are shown in Fig. 6 to give much more consistent temperatures than the air plasma.

It can be seen from Fig. 6 that the effect of reducing the equilibrium concentration of NO is to shift the continuum curve to higher temperatures and the band curve to lower temperatures, the greatest shift being given by the 79% N_2 - 21% O_2 plasma in local thermal equilibrium without NO present. Since a further shift in the direction of higher temperatures is not possible from the standpoint of the absence of the NO reactions, the only way that temperatures determined from the two species of radiation can be brought into agreement is by reducing the value of the calibration constant k in the empirical formula. A reduction of k from 2.2×10^{-48} to 1.3×10^{-48} was required to bring consistency into the temperature determination.

Using the adjusted k value and equilibrium number densities for N_2 and O_2 plasmas obtained by extrapolation of Drellishak's[3] equilibrium compositions to higher pressures, the corresponding $\epsilon = kN_2N_e$ curves for mixed N_2-O_2 plasmas at 10 and 20 atms static pressure were constructed. With these curves the radial emission coefficient profiles of Fig. 5 were converted to radial temperature profiles as shown in Fig. 7. The error flags on the 10 atm profile correspond with the maximum fluctuation in the two intensity profiles measured at the beginning and end of the low pressure run.

A composite plot similar to Fig. 6 has been made in Fig. 8 for the mixed N_2-O_2 and equilibrium air plasmas at 10 atm static pressure.

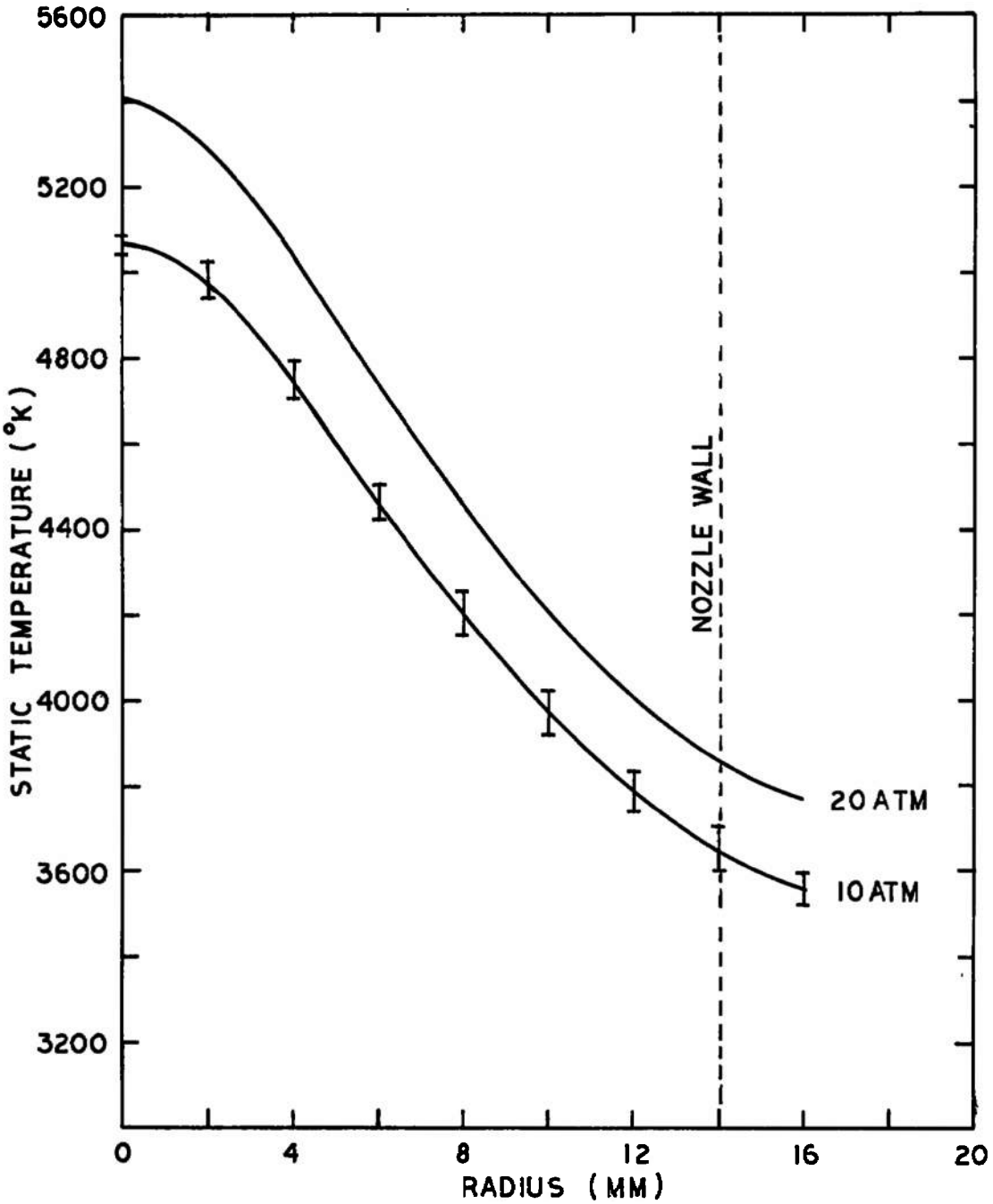

Fig. 7. Radial temperature profiles determined from profiles of Fig. 5; error bars represent temperature variations resulting from fluctuations of Fig. 4.

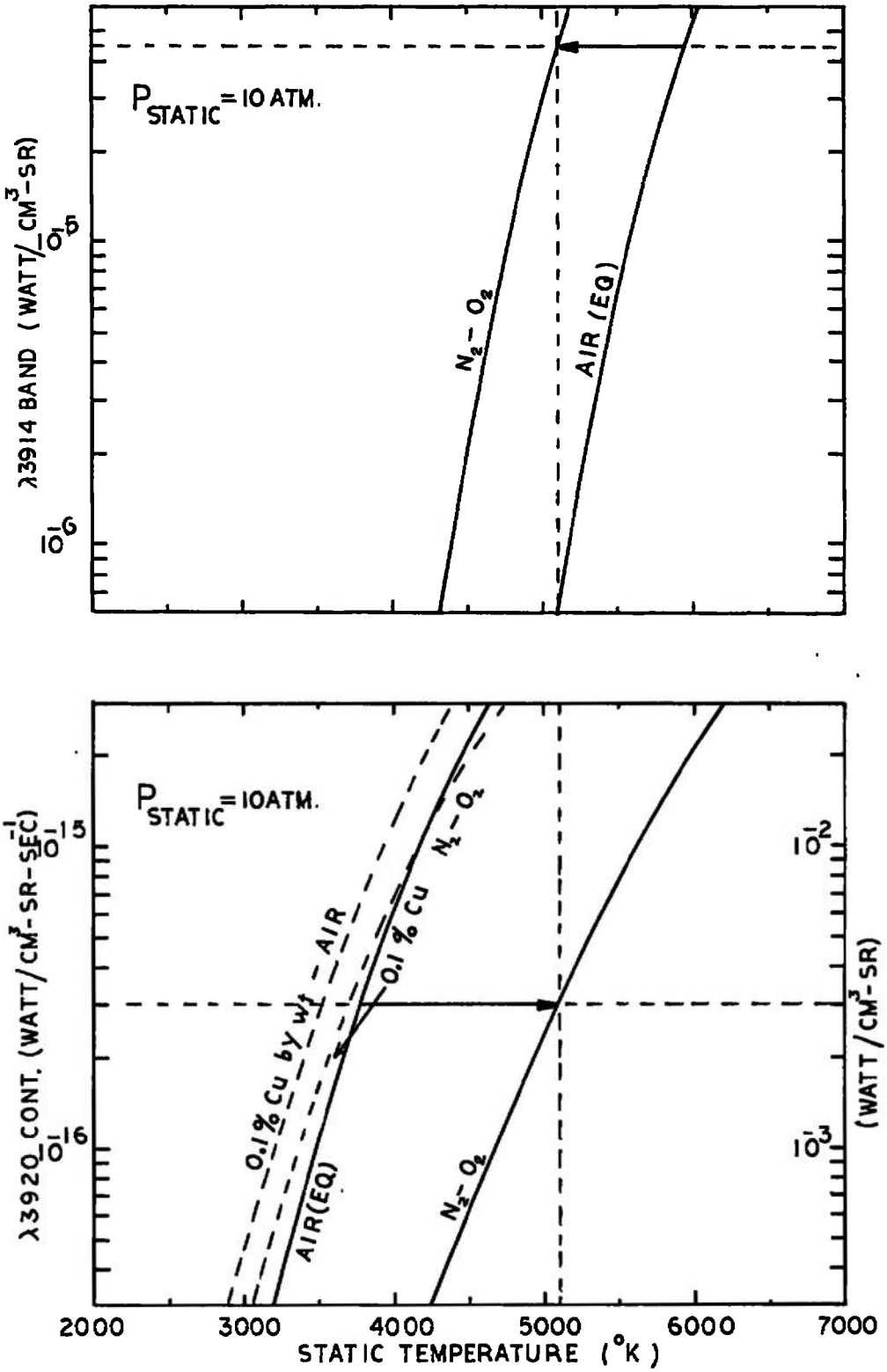

Fig. 8. Comparative plots of band system and continuum for 10 atm air and nitrogen-oxygen plasmas.

The continuum emission coefficient measured on the jet axis is indicated on the lower plot. The axis temperature of 5100°K extended to the band curve indicates that the intensity of the band system is an order of magnitude lower than that of the continuum and certainly should not have been expected to be observed. The equivalent level of the continuum indicated on the lower plot for the 28 Å slit width is $\sim 3 \times 10^{-4}$. Based on the air curves the axis temperature would have been reduced to 3800°K from the continuum and increased to 5950°K when determined from the band (were it measurable).

In order to assess the effect that an appreciable amount of copper, treated as an impurity in the plasma, might have on the estimated calibration curves for the air and N_2-O_2 mixed plasmas, the computed compositions of copper vapor in an inert gas given by Bowen[5] have been used. Estimates have been made of the total number of free electrons present under the very extreme condition of 0.1% by weight of totally evaporated and uniformly mixed copper in the 10 atm plasmas. For this estimate the electron number densities taken from Bowen's work have simply been added to those computed for the equilibrium plasmas. The ratio of the total N_e to that of the clean plasmas have been used to correct the 10 atm calibration curves of Fig. 8 for the effect of this impurity. The results show that even in this very severe case the temperature error resulting from the neglect of such an impurity in the equilibrium air plasma is at most 300°K.

In the case of the assumed N_2-O_2 mixed plasma the copper impurity seems to be much more effective. It would seem that the electrons missing due to the absence of the NO can be replaced by the copper impurity thus making the mixed plasma, in so far as the continuous radiation is concerned, appear as an air plasma in chemical thermal equilibrium in which case the measured axis temperature would be reduced from 5100°K to 3800°K. Past experience with seeded[1,4] plasmas has demonstrated the difficulty of obtaining uniformly evaporated seed material in amounts of this magnitude and thus led one to assume that the effective level of such impurity in the vapor state is considerably lower.

In the event that the copper impurity is actually more serious than has been estimated, the copper line ratio $\lambda 5253/\lambda 5106$, which has also been calibrated as a function of temperature by Bowen, can be used as a substitute for the continuum in temperature measurements. Furthermore, approximate temperatures determined from the copper lines and from the continuum could be used with the measured absolute emission coefficients of the copper lines to determine the level of impurity to about a factor of 2 accuracy. By iterative methods the temperature and impurity level determined from experimental data can be improved.

Bowen has tabulated the computed emission coefficients for both of these copper lines which at temperatures above 3500°K should be observed above the continuum at the above impurity level. At 5000°K the copper lines should be nearly two orders of magnitude higher than the continuum. Under such conditions the plasma should exhibit an almost uniform green color which has not been observed in the high speed color films of the plasma stream. Unfortunately time during this brief set of tests did not permit a complete spectral surveillance of the jet stream.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

From the brief series of tests made on the high pressure FDL air plasma it can be concluded that temperatures as low as 3000°K could be measured with the existing spectral probe. The arc heater operating with an exit static pressure of 20 atm shows a static temperature profile ranging from 3800°K at the edge to 5400°K at the center. When the exit static pressure is reduced to 10 atm this temperature profile ranges from 3600°K to 5100°K. These temperatures were determined under the assumption of local thermal equilibrium and a negligible amount of NO and copper vapor in the plasma. Time did not allow the study of fluctuations or the influence of impurities on the measured temperatures.

It is recommended that a traversing continuum probe, based on the existing calibration curve for the N_2-O_2 mixture, be installed on the 50MW FDL facility for routine monitoring using the existing FM tape recording systems. The scanning rate of this probe could easily be increased to obtain a complete radial profile in times of the order of a second. The spectrographic probe should be used further to establish the copper impurity level in the facility. A companion program should be initiated for the purpose of accurately calibrating the temperature dependence of the continuum in atmospheric pressure subsonic air jets in the same manner as has been done at PSL for the nitrogen jet. The results should be tested for applicability to supersonic streams and finally extended to apply to high pressure supersonic streams. Such a program could be executed with an arc heater at a considerably lower power level.

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13. ABSTRACT

Temperatures in the free stream of the 50 MW Electrogasdynamic Test Facility at WPAFB have been determined from experimentally measured radial intensity profiles of the electron continuum. Static plasma pressures were 10 and 20 atm in flowing air and measured temperatures ranged from 3800°K to 5400°K. A spectral probe defined by the optical path of a 1/4 meter grating spectrograph and focussing lens was traversed across the shock cone of the plasma before and after insertion of test samples. Calibration curves for the detector which were previously developed under the parent contract were used for relating the measured intensity to temperature. The results indicate that the nitric oxide concentration in the plasma is lower than the equilibrium value expected at these temperatures.

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